Intentions, expectations and institutions

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Intentions, expectations and institutions: engineering the future of synthetic biology in the US and the UK

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Abstract

Synthetic biology is a field in-the-making: a loosely-defined amalgamation of diverse disciplines, institutions, and practices. Where some practitioners identify as scientists, others consider themselves engineers; while some extol the simplicity of standardised biology, others dismiss it as counterproductive. Three different communities in synthetic biology (epistemics, sceptical constructors and committed engineers) can be distinguished by way of their intentions, practices and promises.

Synthetic biologists' promises shape policy-makers' expectations, which in turn shape institutional arrangements. These institutional arrangements then influence practitioners' promises in an iterative fashion. In both the US and the UK, 'committed engineers' have succeeded in gaining support for an engineering-based and industry-centred vision of synthetic biology, which promises applications and economic growth. This group's intentions and promises have influenced policy-makers' expectations, which, in turn, have driven the major institutional developments in synthetic biology in the two countries.

However, while the promises of the economic potential of this vision of the field have been embraced at policy levels, other aspects of this vision, such as the importance of enabling infrastructure, are often overlooked. In a sense, committed engineers' promises and rhetoric have been too successful, because they have overshadowed the institutional and infrastructural developments needed to make them a reality.

Keywords: synthetic biology; promissory rhetoric; expectations; engineering

Introduction

Synthetic biology is an archetypal emerging research field. It is young—the first conference was not held until 2004—and it is interdisciplinary, bringing together biologists, engineers, chemists and computer scientists, among others. Importantly, it is promissory and future-oriented: synthetic biologists and policy-makers promote it as the foundation of a new, revolutionary biotechnology and an accompanying industry. The promise of future success helps synthetic biologists gain scientific, social and political commitment, investment and capital. Promises and expectations have been and continue to be crucial in establishing the necessary foundations for this new field, just as they have been and are for other emerging fields (Brown and Michael, 2003; Hedgecoe and Martin, 2003).

In this paper we examine how synthetic biology, which is currently unsettled and fragmented, is in the process of being shaped by a particular set of powerful promissory arguments. These originate in the United States, and have been taken up in other national contexts, particularly the United Kingdom. Our concern is with the relationships between scientists and engineers' intentions and promises, policy-makers' and funders' expectations, and the institutions established to realize synthetic biology.

We ask four interwoven questions: how do scientists and engineers' intentions and promises help to define different communities of synthetic biologists? How does promissory rhetoric shape policy-makers' and funders' expectations? How do these expectations lead to particular institutional arrangements? How do these institutional arrangements in turn reinforce particular promises and expectations and promote certain communities of synthetic biologists above others? Using original empirical research, we demonstrate that practitioners' promises that synthetic biology will deliver predictable, reliable engineering with living things shape policy and funding expectations, which in turn shape the field's dominant institutions. Once established, those institutions reinforce particular forms of synthetic biology over others in an iterative fashion.

We start by presenting an overview of research from the sociology of expectations and related fields. We then outline the field of synthetic biology and describe our empirical research—a comprehensive study involving qualitative interviews, ethnographic observation and reviews of the technical literature. Drawing on our empirical findings, we set out a three-way categorisation of synthetic biological communities, distinguished by differences in their collective intentions and the resultant promissory rhetoric. Crucially, intentions underlie the degree to which synthetic biologists engage with a vision of the field as one of so-called authentic engineering.

We then present our empirical findings. First, we demonstrate how practitioners' intentions shape their promissory rhetoric—some of which emphasises the delivery of applications and economic growth. Second, we show how promises trigger particular expectations from policy-makers and funders in the US and the UK, who develop funding schemes and support institutional arrangements in concert with those expectations. Third, we examine how institutions that exist and are being built in the US and the UK to reinforce the engineering-oriented strand of synthetic biology. That is, there exists an iterative dynamic between intentions and promises in the lab, expectations at the level of policy, and institutions established to fulfil those expectations. We end by suggesting that the success of the engineering vision might, ironically, end up stifling the development of vital infrastructures that are central to this approach to synthetic biology.

Promises, expectations and synthetic biology

Promises and expectations

Work in the sociology of expectations has shown that future-orientation is central to new scientific and technological fields (Fortun, 2005). If a new field is expected to succeed, the more people will invest in it, which means it will be more likely to succeed. It is in this sense that expectations can be performative; the supposition that something will occur can bring that something into existence. Practitioner discourse, such as promissory rhetoric, can shape policy-makers' and funders' expectations. The expectations can in turn have material implications in terms of funding, organisation and resources (Borup at al., 2003; Brown and Michael, 2003). For practitioners to utilise promises in this manner, they must not define them too narrowly. In fact, Eames et al. (2006) argue that 'the interpretive flexibility of a technological "guiding vision" is key to its rhetorical power and appeal in agenda building' (p. 367).

A feature of expectations that is particularly relevant for our analysis is that they work at different levels simultaneously. As Borup et al. (2003) show, expectations play an important role in mobilizing resources at the macro level of national policy programmes, at the meso level of innovation networks and 'at the micro-level within engineering and research groups and in the work of the single scientist or engineer' (p. 286). In our investigation of synthetic biology, we trace the making and moulding of expectations from the level of the synthetic biologists we interviewed (where intentions shape promissory rhetoric)through to the level of national policies in the US and the UK (where promises help define policy-makers' and funders' expectations), to institutional arrangements (where expectations take organisational and material form). We then discuss how macro-level institutions reinforce promises at the micro- and meso-levels of synthetic biological work.

The influence of expectations at the policy level, especially with regard to funding priorities and schemes, and the influence of expectations on institutional arrangements, are particularly relevant to our case study. Birch et al. (2012) highlight the policy ramifications of expectations by pointing out that 'even though future visions might not necessarily achieve the expected technoscientific outcomes, promotional efforts can reshape institutional and policy frameworks' (p. 1). Another feature of their analysis that resonates with ours is their observation that expectations are not only technological, but can also be economic. In their study of the knowledge-based bio-economy they show how expectations are used to argue that 'innovative bio-based products will resolve the societal problem of European market competitiveness, thereby increasing economic growth and general prosperity' (p. 11). The emphasis on economic promises, as we will show, is crucially important in synthetic biology. This reflects a more general trend— 'the relentless influence on economic drivers that dominates research policy' (Nuffield Council, 2012, p. 104)—which means that economic arguments tend to trump others in policy contexts.

A final component of the literature on promises and expectations that is useful for our analysis is the notion of 'compressed foresight'. This was introduced by Williams (2006), in the context of STS work on nanotechnology. Here we use it more broadly to apply to the 'mechanistic understandings of technology trajectories and their "impacts"' (p. 342) common in innovation discussions, which tend to portray futures as 'largely determinate and imminent', to such an extent that on some occasions 'the future is compressed into the present' (Williams 2006, p. 328). As we will argue below, the promises made by certain strands of synthetic biology lead to expectations on the part of policy-makers. Those expectations in turn lead to pressures on synthetic biology to deliver applications and economic growth within very short timescales. That is, there is 'compressed foresight' at the policy level that follows from the success of particular promissory rhetorics in synthetic biology.

Crucially, we draw a conceptual distinction between 'promises' and 'expectations.' The first term we use when referring to synthetic biologists' rhetorical statements about what the field can deliver and what it will become if supported appropriately. The second term we employ when discussing policy-makers' and funders' suppositions about the products and influences of synthetic biology. This heuristic distinction is comparable to Brown and Michael's discussion of scientists' 'forceful public expressions of promise' (2003, p. 16) and the expectations those promises seed in other communities, like those of investors. Borup et al. also conceptualise promises as consensual commitments that trigger and shape the making of expectations (2006).

We view both promises and expectations as contingent phenomena: collectively formulated and established, shaped by contextual particularities, and never incontestable. This position is one supported by Borup et al., who note that 'promissory commitments' are one component of practitioners' 'shared agenda.' (2006, p. 289). Promises and expectations can and do change, just as do shared agendas; neither implies total certainty.

Importantly, we do not posit a linear relationship between promises and expectations. Though practitioners' promises may trigger policy-makers' expectations through such things as funding applications, the latter in turn mould what practitioners go on to promise and pursue. An important aspect of this is institutional arrangements, which are often enabled by funding from policy-makers and which help orient and structure what practitioners do and what promissory rhetoric they deploy. Stated simply, promises, expectations and institutions shape each other.

Promises and expectations in synthetic biology

In the broadest of senses, synthetic biologists hope to improve tools and techniques for manipulating biology at molecular and cellular levels. The reasons for and ways in which researchers hope to accomplish this differ as do the requisite institutional and material demands. This means that synthetic biology remains highly fragmented in many ways. First, scientists and engineers who consider themselves to be doing synthetic biology, and observers of the field like us, use the term without consistency. Second, those involved in synthetic biology constitute a disparate population of scientists and engineers, often with no common background in training and professional experience. As such, different communities within synthetic biology conceive of and practice their work in correspondingly dissimilar ways.

Later in the paper, we present some ongoing research projects that fall under the heading of synthetic biology. Nonetheless, a few examples here may serve to familiarise the reader with the type of work often associated with the field. As its title suggests, *synthetic* biology generally involves the making of new or artificial biological components or systems. Some of this work is pursued to enable greater understanding of natural phenomena. For example, Elowitz and Leibler's (2000) 'repressilator' is a genetic construct capable of inducing oscillatory behaviour in host organisms. The repressilator works as a model system for exploring natural time-dependant behaviour in biology, such as circadian rhythms. Other researchers have sought to introduce novel functionality into organisms to build such things as biological logic circuits (Lederman et al., 2006) or genetic memory-storage devices (Ajo-Franklin et al., 2007). Novel functionality is closely associated with research that aims to deliver specific technological products. Here the goal extends beyond the construction of technologically-functional biological systems to include concern for industrial utility. The Keasling group's work with yeast capable of producing chemical precursors to artemisinin, an anti-malarial medication, is the most well-known of these projects (Ro et al., 2006). Last, a number of researchers are working to develop so-called foundational technologies. These include new tools for synthesising genetic sequences, but also involve mechanisms for standardising functional genetic modules and for measuring the performance of such modules (Lucks et al., 2008). Thus work in synthetic biology ranges from furthering biological understanding to delivering technological infrastructures for designing and building with living things.

In recent years, there has been a proliferation of literature commenting on synthetic biology. From 2004 to 2010, a large number of reports were published on synthetic biology and its social and ethical dimensions (Zhang et al., 2010 list 39 reports published in this six year period). This grey literature mostly treads the same ground—rehearsing concerns about biosafety, biosecurity, intellectual property, the creation of life and public engagement. More recently, philosophers, sociologists and anthropologists have been producing more innovative work on the field. To give a few examples, philosophically-oriented research such as O'Malley (2009) points to the difficulties of engineering living things, and the reality of less sophisticated 'kludging'. Sociological investigations of synthetic biology have been carried out in the context of water engineering (Balmer and Molyneux-Hodgson, 2013), and on the negotiations surrounding the development of standardised biological parts (Frow 2013). Extended ethnographic work on synthetic biology has taken place in research centres in the UK (Finlay, 2013) and the US (Rabinow and Bennett, 2012). Work on applications is less common, but MacKenzie (2013) explores the production of next-generation biofuels and the entanglement of synthetic biology with its geopolitical context. Other research has examined novel features of the governance of synthetic biology (Zhang et al., 2010; Meyer, 2013), and Oldham et al. (2012) provide a useful bibliometric mapping of the field.

The work that is perhaps closest to ours is Kastenhofer (2013), which distinguishes four different stances towards synthetic biology (contemplative, interventionist, constructionist, and creationist). However, Kastenhofer is not primarily concerned with synthetic biology researchers' intentions and promises, how these shape policy-makers' and funders' expectations, and the institutional arrangements that are brought into being, as we are here.

Investigating synthetic biology

This paper is based on an extensive empirical investigation of synthetic biology, involving interviews, ethnography, and a review of the technical literature.

We carried out 48 in-depth interviews with synthetic biologists at universities in the United States, the United Kingdom, continental Europe, and Japan. For this article, we draw from our US and UK data, although our overview of the field is informed by our broader investigation. We sought to interview a wide spectrum of scientific and technological practitioners in synthetic biology. Since synthetic biology is an unsettled field, such things as disciplinary identity, boundaries and relations with existing fields, and collective ambitions are contested by scientists and engineers. As such, we employed self-identification with synthetic biology as our key selection criterion for interviewees: we visited laboratories which embrace the label of synthetic biology and define their work accordingly, and interviewed individuals who do the same. Many of our interviewees are senior figures such as professors and principal investigators, but we also talked to doctoral and postdoctoral researchers. Our interviews covered a host of issues relevant to the making of this field, including synthetic biology's purpose and potential. We found that the interviewees were keen to assert both their own understanding of the field, as well as their view of its transformative potential (or lack thereof).

We also carried out participant observation in a variety of spaces, including research laboratories, international conferences and policy groups. One of us (Schyfter) carried out a long-term (18-month) embedded residency at a synthetic biology laboratory in the United States. A second form of participant observation consisted of membership in research networks and policy groups. For reasons of space, we do not draw directly on this data here, but these experiences have been important in framing our understanding of synthetic biology and its promissory rhetoric. Finally, both of us have participated in key synthetic biology conferences, competitions and workshops.

In order to supplement our interview and observation data, we surveyed a variety of documentary sources. Most importantly, we reviewed the field's publications. These include technical publications, review articles and opinion pieces, as well as the associated policy literature. We also make use of relevant publically-available data, such as institutions' mission statements, research calls and websites.

Epistemics, constructors and engineers

Because of the field's heterogeneity, there have been numerous attempts to categorise the range of activities that fall under the heading of synthetic biology. We introduce these to provide some background to our empirically-based categorisation. Endy (2005), a leading synthetic biologist, divides the community into biologists, chemists, re-writers and engineers. Biologists aim to understand natural phenomena, chemists hope to enable better production of chemicals through metabolic processes, re-writers seek to alter natural biological systems along the same lines as existing genetic engineers, and engineers seek to enable new, more rational tools and techniques for building with biology. Endy's concern for group intentions aligns with our own, as does his focus on different groups' commitment to engineering 'authenticity'. Nonetheless, our categories differ.

Some social scientific work on synthetic biology has focused similarly on categorisation. In a previous literature-based study, one of us identified three types of synthetic biology: DNA-based device construction, genome-driven cell engineering, and protocell creation (see O'Malley et al., 2008). Those involved in the first type of work seek to develop component parts in order to assemble ever-larger devices and systems. The second branch of research involves those working with entire genomes, either by simplifying them to produce minimal cells or by synthesising *de novo* genomes. Finally, protocell work (often excluded in reviews of synthetic biology) seeks to construct cells entirely from scratch using basic chemical components. As with Endy's, this classification is based on group intentions and routine practices. In contrast to both these categorisation schemes, the distinctions we put forward in this paper are based on our analysis of empirical data.

We observed important differences in synthetic biologists' intentions and promises. The most significant divergence concerns the field's rhetoric of and commitment to systematic engineering—the extent to which synthetic biologists see their field as one seeking engineering status. Researchers' commitment to the engineering vision shapes their promises, which shape policy-makers' expectations and, in turn, the institutions established for the field. As we have noted, those institutions have an iterative relation to practitioners' intentions and promises.

We classify synthetic biologists using three labels: epistemics, sceptical constructors and committed engineers. The code names for our respondents reflect these distinctions. Our three categories are our own analytic devices, but they originate from the empirical material we gathered. Importantly, terms like 'sceptical' and 'committed' reflect how much each group embraces the engineering vision and attempts to develop engineering practices. We chose to focus on researchers' relationship to the engineering vision because it appeared repeatedly during interviews and participant observation, and because this rhetoric permeates the field's literature. We then examined how practitioners relate to that vision, and found three general tendencies. Thus while our typology consists of three ideal types, each is grounded in empirical observations and represents an important constituency in synthetic biology. We think that our labels are analytically useful in that together they help elucidate the relationships between practitioners' intentions and promises, policy-makers' and funders' expectations, and institution-building.

Our categorisation is based on our respondents' commitment to the engineering vision. Interestingly, it does not map neatly onto disciplinary background. Engineers, informaticians, biologists and chemists are found in all three of our groups. However, we find that the epistemics tend to be dominated by chemists and biologists, the sceptical constructors by biologists, chemists and engineers, and the committed engineers by a mixture of engineers and (more surprisingly) biologists.

Intentions and promises

Our research demonstrates that epistemics, sceptical constructors and committed engineers understand themselves, their work and synthetic biology in markedly different ways. Most importantly, each group aims at different ends and promises different outcomes. Where epistemics seek knowledge, the other two hope to build. While committed engineers aim to develop engineering-based practices, sceptical constructors remain agnostic.

These differences matter because intentions shape the promissory rhetoric that is employed, and the type of field synthetic biology is subsequently expected to be. Those who distance themselves most from engineering-based approaches to synthetic biology—the epistemics—are also those who are least committed to the field's transformative potential. Similarly, while sceptical constructors often voice opinions that synthetic biology will contribute greatly to the life sciences and biotechnology, they rarely do so with the consistency of committed engineers. While both sceptics and committed engineers promise deliverable products and economic growth, the former do not link such promises to an engineering vision, as do the latter. Consequently, they do not emphasise the need for the new, specific institutional arrangements and infrastructure that committed engineers value and which we examine here.

The committed engineers and their attempts to make biology into an engineering discipline have drawn the most attention from commentators (e.g. Finlay 2013), so we choose to begin with those most commonly overlooked: the epistemics.

The epistemics

We label our first group the epistemics because its members aim to develop scientific knowledge claims, rather than technological products. There is far less concern for applications, and discourse on the making of a new engineering field is almost entirely absent in this group, as are promises of a bio-engineering revolution.

The distinction between epistemic and utilitarian end-goals is described by a UK-based interviewee as the 'split between people who want to solve biological problems and those who want to understand how things work and how you can generate new tools' (Epistemic2UK, 19/08/10). This interviewee's research focuses on using synthetic biological techniques to further scientific understanding of Turing pattern formation in natural systems. He does not dedicate any considerable attention to developing technological products. Instead, he employs and produces tools with the aim of arriving at new knowledge of plant morphogenesis—the process by which morphological differences develop. Sophisticated imaging technologies, computational modelling, and genetic transformations are used to resolve gaps in understanding.

Another, similarly-minded UK-based practitioner explains: 'We don't start off with an application in mind, we'll start off with an interesting biological phenomenon that we want to understand' (Epistemic6UK, 05/12/11). This scientist uses synthetic biology as one tool in a repertoire of methods to study why proteins fold in particular shapes—an important question for the life sciences and chemistry. Again, technology is not a key goal for the laboratory. Instead of desirable products, epistemics identify compelling questions and pursue answers.

For epistemics, the same form of scientific curiosity motivates synthetic biology as it does the traditional life sciences. The promises associated with this new approach revolve around novel tools for increasing our understanding of biological systems. This understanding is served by making, but making is never a goal in itself. For example, Epistemic3UK, refers to knowledge-making practices in synthetic biology as 'learn[ing] by changing' (19/08/10). Innovative tools from synthetic biology, such as new techniques for constructing and combining genetic elements, support the pursuit of new understanding, just as any other laboratory instrument does. Epistemic1UK and Epistemic1US both note that building genetic circuits—synthetic genetic constructs—can serve epistemic ends. Epistemic1US says explicitly that he builds such circuits in order to 'understand how the things really work' (18/08/10). Although his research aims to develop biological equivalents to electronic switches (specifically a two-state switch), this work is intended to produce new knowledge.

Unlike sceptical constructors and committed engineers, epistemics display an uneasy relationship to synthetic biology. Frequently, they self-identify as marginal participants in the field. Indeed, many epistemics are reluctant to self-categorise as synthetic biologists at all, or do so with qualifications. For example, Epistemic4US notes that her work on computational tools for biological science and engineering probably does not 'fall under the umbrella of what is commonly known as synthetic biology' because she is 'trying to understand' rather than deliver a product (22/07/10). Although interested in developing tools for modelling—an important component of contemporary work in biotechnology—her motivation for doing so is to resolve questions about spatial orientation and polarisation in single-celled organisms. Her laboratory is a member of the US's principal synthetic biology research network, SynBERC, and she is classed as a synthetic biologist by other members of that network, but her detachment from utilitarian end-goals presents a difficulty for her self-identification with the field. Many epistemics we interviewed articulated similar views.

The rhetoric of systematic engineering often centres on real engineering practice. This in turn is regularly construed as the use of established engineering principles and practices (Andrianantoandro et al., 2006; Heinemann and Panke, 2006). These principles include the development of engineering infrastructures, particularly the construction and standardisation of modular components, predictable and systematic design, and the decoupling of design and fabrication (Endy, 2005). We found that epistemics often questioned the viability of such engineering principles, a doubt not shared by the committed engineers we discuss below. Epistemic5UK, a scientist concerned with discovering fundamental design principles in evolution, expressed a common critique:

> [A]ll the engineering concepts come from say, electrical engineering or mechanical engineering… Whereas, now, we are in a biological domain, where our material is different, our media is different… So, by enforcing all their ideas you have in this domain, maybe you are limiting yourself. (21/03/11)

In a similar vein, a US-based scientist argues that building with biological materials may demand tools not found in traditional engineering. He says:

> But I guess…you also have to think about what are the best tools to engineer biology? And I don't necessarily think they're the same tools as you would want to design a bridge, right? (Epistemic6US, 13/05/10)

Sceptical constructors

In synthetic biology review articles, science-focused practitioners are often contrasted with engineering-focused ones—those seeking to make artefacts, rather than to understand existing entities and phenomena (see e.g. Church, 2005; Endy, 2005). Our interviewees made similar distinctions, particularly when emphasising their own commitment to making. Constructor2UK, a self-styled maker, argues that the key questions in synthetic biology are: 'what can I build? What can I do? What can I make?' He argues that this penchant for construction sets synthetic biology apart from the work traditionally done by the life sciences. He says, 'I think the transition is that you now are talking about building stuff out of biological materials rather than studying natural systems'. Correspondingly, his labwork aims at producing medical technologies. For him, makers want to 'direct [the] development of a design of a biological system' (21/09/10). Our research suggests that makers can be further divided into two groups; the first of these we call sceptical constructors.

Sceptical constructors accept the notion that synthetic biology is oriented toward making functional things. However, this acceptance is qualified. Although driven by a utilitarian imperative, sceptical constructors remain unconvinced that engineering principles and rational design are necessarily the right approaches to making with biology. Some are not simply neutral, but disagree that living things can be engineered as are existing technologies. Constructor1US finds value in the potential for synthetic biological technologies, and works at building novel systems. Her research is oriented toward making an inter-cellular communication system--a mechanism for transmitting messages from one cell to others (often in the form of antibiotic resistance). Thus, her goal is the successful construction of a technologically functional biological system. To do so, she uses many tools associated with synthetic biology. However, she questions the success of using engineering as a model for the field because:

> We don't know enough about biology to have it be perfect, like a piece of steel can be made perfect. We don't know what the rules are. (24/06/10)

Constructor4US shares her perspective and argues that crucial differences exist in making with the living and engineering the inanimate. Currently, he works for a biotechnology company seeking to transfer university research into the market by way of technological products. The goal of making functional products is central to his work. However, within such a setting, allegiance to strict engineering principles is superseded by a drive to succeed in making. This attitude is shared by all sceptical constructors, who tend to begin from a place of agnosticism about engineering principles, although they usually admit more optimism than do epistemics. They may be sceptical, but they are not wholly doubtful. For example, Constructor5UK says, 'it is not even clear yet, that it is really possible to do proper engineering based design with biological systems, in any kind of, repeatable, reliable, efficient fashion' (02/06/11). An engineer with a specialisation in control theory, he is exploring the *possibility* of applying control expertise to the making of biological technologies.

Sceptical constructors are *show me* synthetic biologists. That is, they are willing to accept the potential of an engineering-based approach, but demand proof of its value: show me that it works. This stance often affects how they view engineering-driven research in synthetic biology. Constructor3UK, for example, admits the potential usefulness of standard biological parts: physically and functionally discrete modules that can be combined to produce higher-level devices and which are often portrayed as crucial to the engineering-driven vision of synthetic biology (Endy and Arkin, 1999). But while Constructor3UK accepts the possibility of a parts-based future for synthetic biology, he sees this approach as one of many, rather than the only legitimate one. Constructor7US presents a similar but more critical view in saying:

> … it's not like we are all going to agree on certain clockwise twists to a screw, where the things are separated by a third of an inch, so that it fits all around the world. We are all working on different strains, we are all working under different conditions, and so that the idea that this guy is going to behave that way, and now this is a standard part, is a false notion in biology. (12/05/10)

Like Constructor3UK, he values the potential benefits of a parts-based approach, but doubts its viability. For both synthetic biologists, this is not a fatal flaw, since success in making supersedes any desire to mirror existing engineering practices.

Sceptical constructors do not dismiss the craftwork of earlier genetic engineering, nor do they vehemently champion the novelty of synthetic biology. Constructor4US says 'I don't see synthetic biology as really, a revolution, I would say it's more of a, the obvious progression of what we already were working on' (03/11/10). Sceptical constructors' intentions may be broadly similar to those of committed engineers—making technological products—but they do not embrace the latter's goal of establishing a new engineering field with its associated institutions and infrastructures. They champion the promise of new biotechnologies, but do not tie this outcome to a specific mode of practice. Making end-products is crucial, but unlike their committed engineer colleagues, sceptics do not demand that this making takes a particular form.

Committed engineers

Unlike sceptical constructors, committed engineers demonstrate little (if any) equivocation about engineering-based approaches in synthetic biology. This group holds firm to the view that rational design and engineering principles can and should form the foundation for this field. Much of this contingent's rhetoric proclaims synthetic biology as real engineering beyond the *ad hoc* craftwork of existing genetic engineering.

The notion that previous genetic engineering is not (in committed engineers' terms) true, authentic, proper engineering is voiced extensively by these practitioners. Engineer3UK, a vocal proponent of synthetic biology in the UK, says:

> [I]f you talk to *proper* engineers, people who actually solve problems, build things, solve application areas… there's a rigour to them and a process, and a quantitative way of doing design, which biologists have never done. (21/09/10, emphasis added)

Engineer3UK also argues that genetic engineers just 'mess around with things,' while synthetic biologists will truly engineer. This attitude is reflected in the type of work undertaken at his research centre, which is broadly geared toward developing foundational technologies and standardised parts for reliable and predictable DNA assembly. Like other committed engineers, Engineer3UK holds to the view that true engineers seek to make future projects easier by introducing tools and techniques to systematise design and fabrication.

Committed engineers tend to self-identify with the label 'synthetic biologist' most strongly. In many ways, this follows from their conviction that the field is fundamentally distinct from existing genetic engineering work. Moreover, this contingent contains the most vocal proponents of synthetic biology. Engineer3UK states:

> I've seen enough of systems that have been designed and built and engineered in living systems that work, to some level, to indicate that this is going to be possible …You know, you would need to be rather Luddite to think that this was not going to revolutionise the whole of biology and engineering. (21/09/10)

Although not all committed engineers dismiss doubters in such stark terms, the group does emphasise the novelty and potential of synthetic biology. They speak the loudest, champion the field with most vigour, and proclaim its potential with the greatest zeal. As we demonstrate below, the promises of systematic engineering with biological things and the delivery of reliable, revolutionary biological technologies provide a compelling narrative that underlies much of the field's success in garnering support.

Arguments are made that the field will drive a revolution and establish biology as this century's technology because it will follow the path of existing engineering disciplines. Engineer2US says:

> [A]t every point during the previous 30 years, we did not see an emergence of coordination of work via standardisation, and we do not see an establishment of decoupling of design and fabrication. And those two things coming together are genuinely new and distinguishable from the first 30 years of genetic engineering. (13/07/10)

As this quotation shows, committed engineers place an extremely high value on the development of new infrastructure, which is portrayed as a necessary foundation for 'authentic' engineering fields. Following our fieldwork, we understand infrastructure to include all support elements that serve as a foundation for systematic engineering work. For example, modular parts serve as basic components for building systems and devices, standard disciplinary practices help coordinate projects and structure work, instruments assist in evaluating designs and testing functional predictions, and fabrication facilities enable design professionals to focus on their task and delegate the construction of materials. Committed engineers are often frustrated by the inadequacy of existing tools and techniques to advance their engineering aspirations, and see new infrastructure development in the form of modular parts, workable standards, rational design tools and support facilities as a key condition of success. For instance, standards for making modular parts and the fabrication facilities needed to assemble those parts with precision and at scale are championed as necessary for engineering work.

Commitments to this engineering vision (and the distinctive promissory rhetoric that accompanies those commitments) shape the institutional arrangements and infrastructural support that become involved in the growth of the field. Intentions to make synthetic biology a branch of engineering, and promises that it will deliver successfully engineered products for industry, demands that particular institutions become established or involved.

Thus intentions not only distinguish contingents within synthetic biology and their promises, they also shape policy and funding expectations, and the institutional arrangements that are brought into being. In turn, institutions encourage particular types of synthetic biological work and reinforce the importance of certain intentions over others. In the following section, we demonstrate how the intentions and promises of the committed engineers instil particular expectations in policy-makers and funders.

[Caption: This striking poster for the Fifth International Meeting on Synthetic Biology can be interpreted in various ways. We see it as portraying three phases of human scientific and technological interaction with living nature. First, through botanical study and representation; second, through molecular biological tools like sequencing; third and last, through engineering standardisation and construction. We think that the final image portrays the future committed engineers envision for their field. (credit: Chrysos Designs, Drew Endy and the BioBricks Foundation)]

Expectations and institutions

The United States and the United Kingdom are two countries with prominent communities of synthetic biologists, committed sources of funding, and institutions associated with the field. We understand the term 'institution' to specify an organisation or association of people intended to serve a specific goal, including any material structures or services necessary to execute those goals. Institutions thus include such things as funding agencies and programmes, research networks and centres, and systems of infrastructure. We argue that institutions are clearly shaped by practitioners' intentions and promises, and policy-makers' and funders' expectations for synthetic biology. As we discuss in the following section, these institutions in turn become important in shaping practitioners' intentions and promises by encouraging them to frame their work according to a particular view of synthetic biology.

The United States

The United States currently has the most laboratories self-styled as working in synthetic biology, the largest number of self-identified synthetic biologists, the greatest amount of research funding dedicated to the field, the most extensive list of publications (Oldham et al., 2012), the longest-standing centres for research, and is home to the field's most vocal (and colourful) proponents—individuals such as Drew Endy, Jay Keasling and J. Craig Venter. The US is also the organisational home of the Synthetic Biology X.0 conference series[1] and the International Genetically Engineered Machine (iGEM) competition—two key synthetic biology events (see Frow and Calvert, 2013 and Balmer and Bulpin, 2013 for further discussion of iGEM).

The breadth of researchers working in US synthetic biology is matched by a diversity in types of work. The US houses every form of synthetic biology discussed above. Nonetheless, committed engineers in the country have worked successfully to frame synthetic biology as an engineering-based venture at the level of national institutions. The field has become defined by application-driven work and an engineering vision. While constructors and epistemics form part of the US synthetic biology community, many operate within the context of engineering-based institutions, and position their work accordingly. The dominant contingent in the US defines synthetic biology as engineering, as new, and as distinct from traditional life sciences. As Constructor1UK observes, synthetic biology in the US has an 'oppositional culture to… conventional biology'. By this, he suggests that US synthetic biology centres on the use of engineering principles and the development of industry-oriented functional technologies, rather than the use of existing methods from the life sciences and the goal of epistemic development. This framing of the field,

[1] http://sb6.biobricks.org/about/series/

we suggest, is a result of rhetorical success by the committed engineers, a particular configuration of key institutions, and the reinforcement of the committed engineers' vision by those institutions.

At the institutional level, we find a focus on the engineering vision embraced by committed engineers. This emphasis on engineering is expressed plainly in the public pronouncements of the principal research network for US synthetic biology at the time of writing: the Synthetic Biology Engineering Research Centre (SynBERC).[2] The laboratory at which Schyfter carried out his 18-month ethnography was a member of this organisation. The centre's website summarises its approach:

> SynBERC's vision is to catalyze biology as an engineering discipline by developing the foundational understanding and technologies to allow researchers to design and build standardized, integrated biological systems to accomplish many particular tasks. *In essence, we are making biology easier to engineer.* (2012, emphasis in original)

SynBERC research ostensibly employs rational design and systematic engineering, as is sought and promised by committed engineers. The Center's research focuses on making parts, devices and chassis; developing testbed technologies with utilitarian functionality; and supporting the development of an engineering infrastructure. That is, SynBERC is meant to enable the making of a new engineering field and the production of functional technologies—precisely the intentions and promises of the committed engineers, and the expectations of policy-makers and funders.

SynBERC's testbeds are specific technological applications of synthetic biology research. They include a 'microbial chemical factory' for producing valuable products (such as biofuels) and a 'tumour killing bacterium'. These target technologies are intended to accomplish three key goals: coordinate diverse practitioners around a shared focus; drive research into the making of an engineering infrastructure for the field; and deliver an end-product. Thus, testbeds are portrayed as accomplishing two key promises of the committed engineers. The first is establishing a new engineering field that features systematic engineering practice based on standardised, predictably functional components. In introducing its testbeds, the SynBERC website states that these will assist in developing and testing the parts and devices that form the 'basis for the field of synthetic biology' (SynBERC, 2013). The second aim is delivering functional end-products. SynBERC notes that testbeds are 'selected based on their interest to [the Center's] industrial partners' (SynBERC, 2013). Research supported by SynBERC is driven by the promise of a 'future synthetic biology industry' (SynBERC, 2013). Thus SynBERC, itself a vital institution in synthetic biology, enrols a second body of key institutions—private industry. Representatives of industry not only attend SynBERC's bi-annual research meetings; they also form part of the administrative council for the Center and influence the direction of investigation through commitments of funding and contributions of advice. These institutions are enrolled because of the engineering-geared vision for the field, and in turn strengthen that vision through their involvement.

In addition to these funding programmes, committed engineers in the US have succeeded in establishing some support facilities for infrastructure for engineering-based synthetic biology. This has not been easy; groups of committed engineers on both sides of the Atlantic have faced the significant challenge of convincing research funding bodies to invest in infrastructure such as standards development, which is not seen as cutting-edge research. Infrastructure-building is not

[2] Funded by the National Science Foundation's Engineering Research Centers programme.

considered to be a venture in furthering knowledge, nor is it a process that will lead straightforwardly to impressive new technologies. Committed engineers complain that epistemics are funded to pursue what they see as bespoke, craft-like projects because these are hypothesis-driven, and fit better into established funding structures. The more mundane work of developing technology platforms is harder to present as novel scientific research. They also complain of funding being diverted to projects that do not seek systematic engineering, but promise to deliver useful products (such as those undertaken by sceptical constructors).

Committed engineers draw parallels with other successful infrastructural initiatives to argue for the value of their endeavours, such as the Internet Engineering Taskforce (see Frow, 2013). The notion of a 'fab' has also proved influential. This term is borrowed from the microelectronics industry, in which it is used as a common name for a semi-conductor fabrication plant. In 2009, the BIOFAB was founded in California as the 'world's first biological design-build facility' with the aim of producing 'broadly useful collections of standard biological parts' (BIOFAB, 2009). Although far from being a biological equivalent of the semi-conductor fab, this was the aspiration. Work at the BIOFAB also included research to produce metrological tools (Mutalik et al, 2013a; Mutalik et al., 2013b)—infrastructure for measurement of parts' behaviour.

One of the most successful arguments used to elicit this type of funding has been to link infrastructure to industrialisation. For example, the White House's *National Bioeconomy Blueprint* highlighted the importance of synthetic biology to the bioeconomy, a sector with 'tremendous potential for growth' (Office of the President, 2012, p. 1). Arguments are made that standards and technology platforms are essential for innovation and scale-up in synthetic biology, often on the basis of parallels with other industrial sectors. The promises of industrialisation have been embraced at the institutional level, and as a result been made real in the form of funding for the type of synthetic biology that makes such promises.

The United Kingdom

The UK has recently committed substantial funding to synthetic biology, and its existing research places it second to the US in terms of numbers of publications (Oldham et al. 2012). As with the US, a diversity of practitioners across our three categories populate UK synthetic biology. Although the UK has been less focused than the US on the engineering vision, an important strand of research is associated with committed engineers. Interestingly, we find that this faction has been influenced heavily by US visions of engineering-based synthetic biology. This may be attributed to trans-Atlantic collaborations between several UK universities and MIT, where key figures in US synthetic biology laid much of the groundwork for current engineering practice and discourse. Engineer2UK, Engineer3UK, and Engineer4UK all spent extended periods of time at MIT, found this framing of synthetic biology very compelling and went on to seed British universities with this particular type of research. These universities were also some of the first UK universities to take part in the field's key international competitions and conferences. Thus in the UK, we find committed engineers' perspectives on synthetic biology similar to those present in the US, due to a trans-national pattern of influence.[3]

The largest centre for synthetic biology in the UK at the time of writing, the Centre for Synthetic Biology and Innovation (CSynBI) at Imperial College London, the dominant discourse is one of engineering. CSynBI, like SynBERC, presents itself as 'developing the foundational tools for synthetic biology and using these to generate innovative biological applications for cutting-edge

[3] Such trans-national patterns of influence are not only found between the US and the UK, but also between the US and the other countries involved in international synthetic biology initiatives.

research, healthcare and industry' (2012). Engineer3UK, a member of the Centre, stresses the importance of developing:

> …a foundational set of technologies and a framework, a construction framework that allows designers to come and build new biological devices without actually knowing intimate details about biology. (21/09/10)

These goals are at the heart of the committed engineers' intentions and promises. Tellingly, funding for CSynBI comes from the Engineering and Physical Sciences Research Council, not the UK's biological sciences funding council. The specific mechanism used supports engineering centres, much like the one used to fund SynBERC in the United States.

The emphasis on utility and industrialisation is central to the work of CSynBI. Engineer3UK, a member of the centre, argues that the 'final product of synthetic biology will ultimately be, I think, industrialisation'. For him, synthetic biology must and will deliver tangible products that have an 'impact on the economic developments of the UK'. That is, his intentions and promises centre on industrialised engineering. This view has been taken up in the policy realm, as in the US. Synthetic biology has been identified by the UK's Technology Strategy Board as 'a key emerging technology with the potential to create a billion pound industry within the UK in the next decade' (Department for Business, Innovation and Skills, 2011, p. 10), and a UK Synthetic Biology Roadmap (2012) outlines the path to future industrialisation.

The UK has also begun to support the establishment of infrastructure facilities along the lines of the US's BIOFAB. There is investment into an 'infrastructure for platform technology in synthetic biology' (EPSRC, 2012a) in the UK, bringing together five universities. The summary of this grant attaches itself to previous successful work in engineering by drawing parallels to James Watt's invention of the steam engine, implying that we are at a similar turning point in the industrialisation of synthetic biology, and implicitly referencing the extensive infrastructure constructed to support steam engine technologies (EPSRC, 2012b). Again, expectations of transformative potential and the engineering contingent's intentions and promises are strongly connected.

The iterative relation between institutional arrangements and practitioner intentions

We have presented a seemingly linear path from practitioner intentions to institutional arrangements. To review: synthetic biologists' intentions shape their promissory rhetoric; this promissory rhetoric in turn shapes policy-makers' and funders' expectations of synthetic biology; those expectations then shape the institutional arrangements established to develop the field. However, one final observation demonstrates that the relationship, rather than being linear, is iterative. Institutional arrangements reinforce particular practitioner intentions.

Intentions underlie the promises made (or not made) by different practitioner groups, and shape the expectations held by policy-makers and funders. Institutions are the material and organisational articulation of practitioners' intentions and promises, and policy-makers' and funders' expectations. Importantly, those institutions are not an end-point. Once established, they reinforce a particular vision of the field's future, mould its members' intentions and promises, and bolster subsequent expectations about what it will deliver. That is, intentions, promises, expectations and institutions shape each other and together point the field in particular directions.

Consider first the case of the United States. SynBERC encompasses labs engaged in research that falls across our tripartite classification of aims, but the character of SynBERC as an engineering centre compels all practitioners to position their work in relation to the engineering ideal. Even epistemics must relate their research to one of the Center's functional testbeds. Thus, the diversity of practitioners' intentions is somewhat obscured by the promise of new field of engineering, the economic expectations of a new industry, and the character of the institutions established to deliver field and industry. At Schyfter's host laboratory, several doctoral researchers were epistemics. Epistemic1US, discussed above, works to further understanding of biological organisms. Nonetheless, he frames his work as the development of a two-state switch, a construct that can have technological functionality. Though his interest is in biological science, he routinely portrays his work as a pursuit of technologies. SynBERC's institutional character, driven by one faction of synthetic biological practitioners, shapes the context for all the work supported by the Center.

Although engineering-oriented institutions do currently dominate in the UK, a broader range of work is funded under the 'synthetic biology' banner. For example, in 2008, UK research councils funded seven networks in synthetic biology. When these grants were awarded and the institutions established, there was a deliberate attempt not to restrict the definition of synthetic biology, but instead to incorporate a wide range of activities and expertise. These included protein engineering, chemistry, control engineering and systems biology—areas populated by epistemics and constructors (BBSRC, 2007). This inclusive approach was not without its critics. Constructor2UK complains: 'when things like this come along there's obvious, you know, research councils are threatening to throw money at it, you know, suddenly everyone and their dog is doing synthetic biology' (21/09/10). This comment captures how institutional arrangements—including funding and centres—can encourage the adoption of particular labels and promote certain types of work.

Discussion and conclusions: engineering the future of synthetic biology

In this paper we have explored the relationships between synthetic biologists' intentions and promises, policy-makers' and funders' expectations, and institutional arrangements in the US and the UK. Following Borup et al. (2003), we have attempted to connect different levels of discussion that are often separated: the intentions that drive research at the laboratory bench and help consolidate groups of similar practitioners, and the institutional arrangements that are the result of policy initiatives. We put forward a categorisation of three types of synthetic biologist derived from our empirical material: epistemics, sceptical constructors and committed engineers. We presented this typology because we think it captures the three most important communities in the field, distinguished by competing intentions of what the field ought to be and promises about what it will deliver. The typology also captures some key causes for the ongoing shaping of synthetic biology in an engineering mould. Building on work in the sociology of expectations (Brown and Michael, 2003; Fortun 2005; Hedgecoe and Martin, 2003), we showed how the committed engineers' success in promoting a particular vision for synthetic biology (an engineering, industry-oriented future) fosters particular expectations from policy-makers and funders. These in turn affect the institutional arrangements established to support the field, such as funding schemes, and research networks and centres. We also noted the iterative influence of institutions on researchers' intentions and promises. We have given examples of this pattern in the US and, less markedly, the UK.

As one looks from epistemics to sceptical constructors to committed engineers, important shifts are observed. A greater focus is placed on, and more faith given to, the principles and practices of engineering. Synthetic biology becomes defined more strictly as the application of engineering principles to biology. There is also a greater demand for new kinds of infrastructure, standards, facilities, resources, and organisational arrangements, and an increased rhetorical emphasis on novelty. More is meant to be revolutionary, more is promised, and more is to be expected. It is not that the committed engineers have a monopoly on promises—epistemics promise greater understanding and constructors promise new products—but committed engineers have powerful arguments for their vision, and they have captured the imagination not only of other scientists and engineers but also of politicians and research funders. Committed engineers draw analogies between their intentions and work, and other engineering fields that are already extremely successful, and they promise applications and economic growth.

These economic promises have been persuasive at a policy level, but this has led to recent concerns among committed engineers about the neglect of other key components of their vision. Most importantly, committed engineers argue that necessary infrastructure-building lacks dedicated funding. Institutions and tools needed to enable the engineering vision have not received sufficient attention and support. For example, funding for the BIOFAB, the dedicated fabrication and testing facility, expired in 2011. Although similar work continues elsewhere (Kelley, 2014), no comparable infrastructure has replaced the BIOFAB. Synthetic biologists in both the US and the UK find themselves under increasing pressure to deliver applications, products and prototypes in the next few years—to deliver on their promises and fulfil expectations. Some argue that funding has been directed towards the quick wins and the low-hanging fruit of 'old-style' genetic engineering. The longer-term project of the committed engineers—a new field and systematic design and fabrication of biological technologies—requires infrastructural work not currently championed by funding agencies. A key type of institutional arrangement has gone unsupported.

In a sense, the committed engineers' rhetoric has been too successful. We noted above that Eames et al. (2006) point to the importance of 'the interpretive flexibility of a technological "guiding vision"' (p. 367). The committed engineers' guiding vision perhaps lends itself to too much interpretative flexibility, since it has been reduced and narrowed to a demand for profitable applications.

In this way scientists and engineers engaged in synthetic biology can be victims of 'compressed foresight' (Williams 2006), in terms of the increased external demands for promised products in a timescale much shorter than we have seen with other, more established, engineering fields. The convincing and successful discourse of engineering-based industrialisation and economic growth can lead ironically to a shift away from the infrastructural development that committed engineers perceive to be necessary to provide the foundations for engineering with biological things.

To extrapolate beyond our case study, what we think we are witnessing is a selective emphasis on the economic aspects of scientists and engineers' promises in policy communities. Like Birch et al. (2012), we have shown how expectations of economic benefits rise to prominence, in this case to the detriment of the requisite infrastructural developments. Although further research is needed on other technologies in different national contexts, we think our analysis of synthetic biology draws attention to an issue that is proving enormously influential on the development and direction of new technoscientific fields: the 'foregrounding and privileging of economic framings in research policy' (Nuffield Council on Bioethics, 2012, p. 52).

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